Intra-Vehicle Wireless Sensor Network Communication Quality Assessment via Packet Delivery Ratio Measurements

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Abstract. For the development of reliable intra-vehicle low power wireless communication protocols, realistic wireless channel models are required. In this article, we present measurements taken in two different vehicles (compact passenger cars), one with a petrol and the other with an electric engine, with the aim to develop such channel models. We measured the received signal strength indicator (RSSI) and packet delivery ratio (PDR) values for several channel and communication settings, e.g. varying IEEE 802.15.4 channels, transmit power levels, packet sizes and different levels of Wi-Fi interference. We observed several unique characteristics of the wireless channel behaviour, resulting in separate zones inside the vehicle with similar behaviour, effects due to different types of engines and observed the impact of charging the electric car.

Keywords: RSSI · SNR · PDR · Intra-vehicle low power wireless communication · Wireless channel behaviour · IEEE 802.15.4

1 Introduction

Recently, there has been increasing interest in intra-vehicle low power wireless communications. The benefits of wireless sensors inside the vehicle are to reduce weight due to reduced cabling, simpler installation (deployment) and easier replacement of the sensors. Additionally, it is possible to customize the sensor installations for individual preferences, such as adding temperature sensors or distance sensors to enhance the basic configuration of a vehicle. This interest in in-vehicle wireless sensor networks has resulted in the development of specialized MAC protocols for this area. In order to develop efficient MAC protocols, we need to be able to accurately simulate a realistic vehicle environment. The most critical requirements in the intra-vehicle environment are short communication delays and high reliability for safety critical applications such as tyre pressure sensing or distance measurements [1]. For this reason it is important to have a realistic channel model or at least a suitable probabilistic packet reception model for the proposed environment. Most of the published research in this area

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has focused on characteristics of the intra-vehicle wireless channel for Ultra-Wideband (UWB) or frequencies higher than 2.4 GHz, see [2–6]. In this paper, we focus on the channel behaviour of intra-vehicle low power wireless communication for a range of different scenarios. The measurements were performed in two different car types, i.e. one with petrol and one with electric engine, and considering the presence of different levels of Wi-Fi interference. The remainder of this paper is structured as follows. The next section presents related work in the field of intra-vehicle wireless channel measurements. Then Sect. 3 presents the experimental deployment which includes the software and hardware platform being used. The experimental setup in Sect. 4 describes the different settings for the sensor communication and the different scenarios for the measurement campaign. The fifth section presents the experimental results and discussion of the observed channel behaviour. Finally, the conclusions provide a brief summary and critical discussion of the findings and give an outlook to future work.

2 Related Work

The intra-vehicle radio channel behaviour for the IEEE 802.15.4 standard in the frequency range of 2.4 GHz has been investigated to a lesser extent when compared to the study of UWB in intra-vehicle scenarios. In [7,8] the authors performed measurements of the channel behaviour inside the car for a small number of nodes with a fixed gateway position. Additionally, the measurements were carried out with a fixed topology and only for a single IEEE 802.15.4 channel with fixed packet size. Conclusions from this measurement configuration are limited to a specific application and cannot be adopted for a broader range of applications with different packet sizes or on different IEEE 802.15.4 channels. The authors in [9], who investigated the coexistence between Zigbee and Bluetooth devices inside a vehicle, also only focus on a small number of nodes to measure the interference. In their work, they consider the channel behaviour for different areas inside the vehicle such as the passenger area and the engine compartment. A broader range of measurement settings is used in [10] to observe the intra-vehicle channel characteristics, but only for one vehicle and without Wi-Fi interference. In [11] the authors measured the intra-vehicle channel characteristics at three positions only, which are not practical positions for wireless sensor nodes inside a vehicle. There is no observation of the different zones inside the vehicle such as the passenger area or the boot. The study [12], which observes the bit error rate (BER) against signal to noise ratio (SNR) performance of UWB systems applied in commercial vehicles includes similar measurements but with a smaller number of nodes and focused on the IEEE 802.15.3a frequency range of 3100–10600 MHz. Beyond these publications, to the best of our knowledge, there is no research that measured the intra-vehicle channel behaviour in the 2.4 GHz frequency band with a similarly wide range of measurement setups and different types of vehicles as presented here.

3 Experimental Platform

The measurements presented in this paper were carried out with the XM1000 wireless sensor node platform [13]. The XM1000 sensor node has an IEEE 802.15.4 compliant Texas Instruments CC2420 radio chip. All recorded Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI) values are based on the technical description of the CC2420 radio chip. We programmed the sensor nodes with the "TRIDENT" [14] firmware, which is based on the "TinyOS" [15] operating system version 2.1.2. TRIDENT provides a fast and simple measurement setup without the need for individual programming of each sensor node for each measurement. In addition, TRIDENT supports over the air upload of the recorded packet information from the nodes onto a back-end server system. This prevents changes in the measurement environment through changing positions or/and antenna orientation of the nodes. In order to compare channel characteristics across different types of cars, we performed the experiments in a 2000 Hyundai Accent GLS (petrol engine) and in a 2011 Nissan Leaf (electric engine).

4 Experimental Setup

For the measurements we placed the wireless sensor nodes at different positions inside the vehicle. The measurements were carried out with a measurement time of up to 5 h for each setting. Figure 1 shows the wireless sensor node position schema inside the Hyundai.

To compare the effect of radio propagation with different types of engines, we carried out the same type of experiments also in a Nissan Leaf (see Fig. 2 for the schematic setup). The smaller number of nodes used for Nissan Leaf is a result of the observations from the Hyundai Accent measurements, which concludes that a reduced number of nodes provides sufficient results for certain measurements. The positions of the smaller number of nodes are based on the results of the measurements with higher number of nodes. It represents the same channel behaviour with a less complex measurement setup. The measured difference between the results from the 19 nodes and the 11 nodes is then 1.32% in the worst case. To observe the effect of the engine when driving, a smaller setup of wireless sensor nodes was used for these measurements (see Fig. 3). The positions of the nodes are chosen to represent different sensor applications: node ID 1 is at the rear view mirror for temperature sensing or light sensor for the auto dip function, node ID 2 and 3 are in the corners of the dashboard next to the wing mirrors for distance sensors or mirror adjustments. Node ID 4 is placed at the bottom of the dashboard for temperature sensing and node ID 5–8 are below or behind the passenger seats to represent the seat belt detection or passenger detection. The distance sensors for the rear are represented by node ID 9 and 10. The nodes ID 12–15 in the engine section represent different temperature sensors or washer fluid level sensor. The tyre pressure sensors are displayed by the nodes ID 16–19. The star mark of the Wi-Fi symbol represents the position of a laptop which generates the Wi-Fi interference by UDP broadcasts with fixed transmit power. All nodes are oriented orthogonally to the side of the vehicle, their USB ports pointing to the left side of the car. All nodes behind the driver door are oriented with the top to the engine section and all other nodes are oriented to the boot section. This setup ensure that the main beam of inverted F Antenna of the XM1000 sensor node is orientated to the middle of the vehicle to reduce the influence of external interference.

Transmit power: In order to distinguish between weak and strong links with varying transmit power settings, we choose a wide range of transmit power settings from 0, −5, −10, −15 to −25 dBm.

Transmission setup: Each node takes turns to broadcast a single packet, which is received by the other nodes. They then record the received packet information as shown in Table 1. This transmission cycle repeats until each node has sent 100 packets for each measurement configuration. The RSSI and LQI values are generated based on the technical description of the CC2420 radio chip.

Selected channel: The 2.4 GHz ISM band is the common frequency band for IEEE 802.15.4 Wireless Sensor Networks (WSN) and for IEEE 802.11 Wi-Fi. The IEEE 802.15.4 channels “11” and “12” overlap with Wi-Fi channel “1” and the IEEE 802.15.4 channels “15” and “20” are located between the typically used Wi-Fi channels “1”, “6” and “11”. This configuration allows us to measure the typical interference created by Wi-Fi traffic on the low power wireless communication. The selected IEEE 802.15.4 channels “15” and “20” are used as non-interfered reference for comparison of channel behaviour with and without the Wi-Fi interference.

Packet size: We varied the packet size of the experiment data from 14, 32 to 64 bytes plus 16 bytes IEEE 802.15.4 specific header data and 2 bytes cyclic redundancy check (CRC).

Packet structure: The packet structure can be seen in Fig. 4.

Wi-Fi interference setup: The Wi-Fi transmit power was varied from 10.0, 4.77, 3.01, to 0.0 dBm and the Wi-Fi traffic was UDP packet based.

Table 1. Recorded values

Recorded packet information	
Sender ID	Packet Sequence Number
Noise level [dBm]	RSSI [dBm]
Link Quality Indicator (LQI)	

4.1 Scenarios

We observed the wireless channel behaviour for different scenarios based on the experimental parameters listed above, e.g. different transmit powers, different

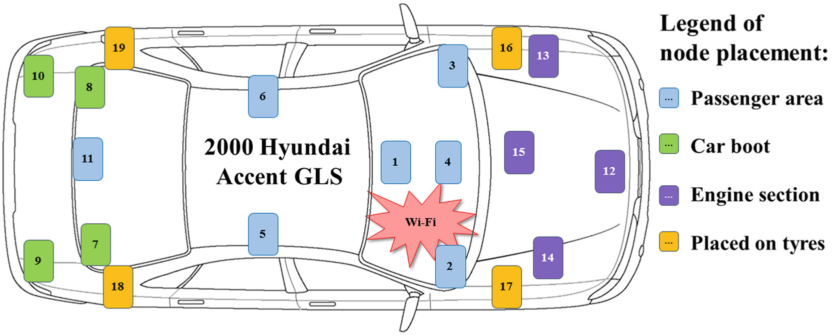


Fig. 1. Nodes placement inside the vehicle.

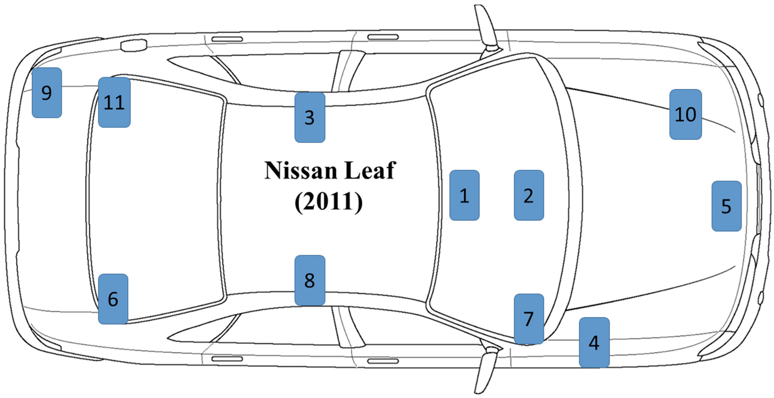


Fig. 2. Measurement setup for the 2011 Nissan Leaf.

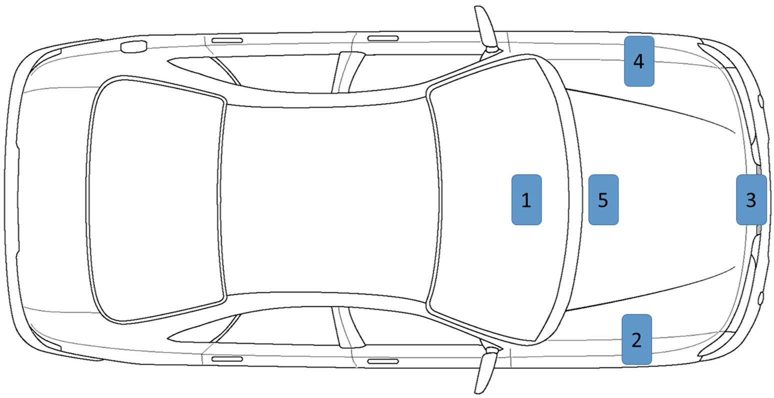


Fig. 3. Measurement setup to observe the influence of the engine types.

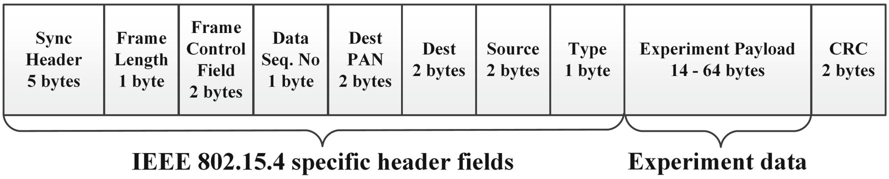


Fig. 4. Packet structure

IEEE 802.15.4 channels, different packet sizes and different Wi-Fi interference level and additionally for the engine measurements the status of the car, such as parking, driving or specifically for the electric car the charging phase after driving. Tables 2 and 3 show the settings used for the different scenarios.

Table 2. Scenarios for the 2000 Hyundai accent GLS:

Scenario no	Driving	Dif. channels	Dif. Tx powers	Wi-Fi interference	Dif. packet size
1	No	Yes	Yes	Yes	Yes
2	Yes	Yes	Yes	No	No

Table 3. Scenarios for the 2011 Nissan leaf:

Scenario no	Driving	Dif. channels	Dif. Tx powers	Wi-Fi interference	Dif. packet size
3	No	Yes	Yes	No	No
4	Yes	Yes	Yes	No	No

5 Experimental Results and Discussion

We present the results of our measurement campaign in the following. We distinguish between results for the Hyundai and the Nissan initially, but also compare them to each other.

Signal-to-Noise Ratio (SNR): The average SNR has been used to compare the various effects of the different zones and the Wi-Fi interference at the low power wireless communication. For the calculation of the SNR value see Eq. 1.

Received Signal Strength Indicator (RSSI): The measured RSSI values contain the average RSSI level during reception of the packets and the RSSI values range is between −100 dBm and 0 dBm.

Noise level: The noise level is measured after successful transmission or reception of the packets over a period of 384µs.

Link Quality Indicator (LQI): The LQI value is calculated by the CC2420 radio chip and based on the average correlation value on the 8 first symbols after the synchronisation header for each incoming packet. The range is between 50 and 110, where 110 represents the highest quality and 50 represents the lowest quality. The CC2420 radio chip does not use the RSSI value to calculate the LQI value because the RSSI can be increased by narrow-band interference inside the channel bandwidth while the interference actually reduces the link quality.

Packet Delivery Ratio (PDR): The PDR is calculated based on all transmitted and successfully received packets from sender to individual nodes without retries.

$$SNR/\mathrm{dB} = RSSI/\mathrm{dBm} - Noiselevel/\mathrm{dBm} \quad (1)$$

5.1 Measurement Results for the 2000 Hyundai Accent GLS

The average SNR values for 0 dBm transmit power and without Wi-Fi interference are shown as point to point connections in Fig. 5 and with a colour map in Fig. 6. The colour map shows the sensor ID of the transmitter on the horizontal axis and the average SNR values of each receiver in the corresponding column. From the groups of similar average SNR values in the colour map, it can be seen that depending on the location of the wireless sensors, the channel behaviour is similar for zones inside the car, such as the boot, the passenger area and the engine section. The different zones are explained in Sect. 5.4.

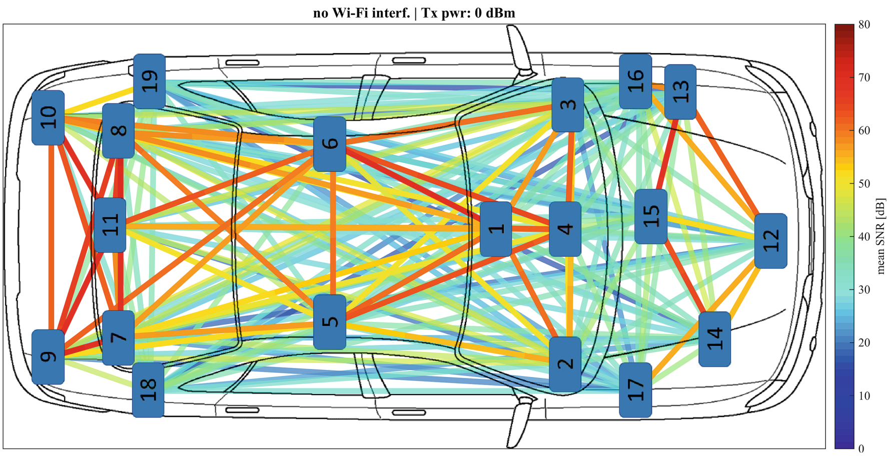


Fig. 5. Average SNR values for the different wireless sensor links for 0 dBm transmit power and without Wi-Fi interference.

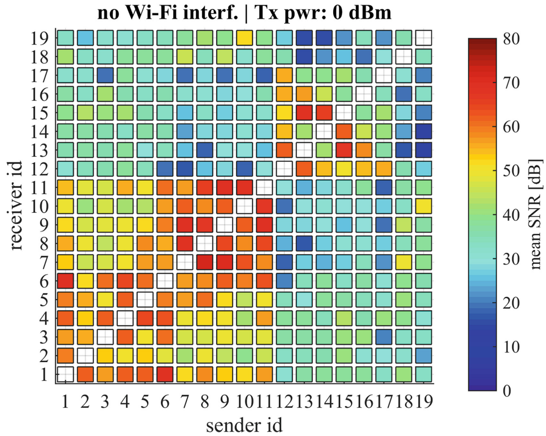


Fig. 6. Average SNR values for the different wireless sensors for 0 dBm transmit power and without Wi-Fi interference.

The effect of the Wi-Fi interference on the low power wireless communication can be seen in the Fig. 7. It shows the 0 dBm Wi-Fi interference at the Wi-Fi channel 1 which overlap the IEEE 802.15.4 channels 11 and 12. The SNR values of the IEEE 802.15.4 channels 11 and 12 is in average reduced by 8.1 dB compared to the low power wireless communication at the IEEE 802.15.4 channels 15 and 20. The PDR of the affected IEEE 802.15.4 channels 11 and 12 is also reduced because of the Wi-Fi interference (see Fig. 8). Especially for all links that originate on the outside of the passenger and boot areas, the PDR decreases on average by 15.1% compared to the PDR of the IEEE 802.15.4 channels 15 and 20.

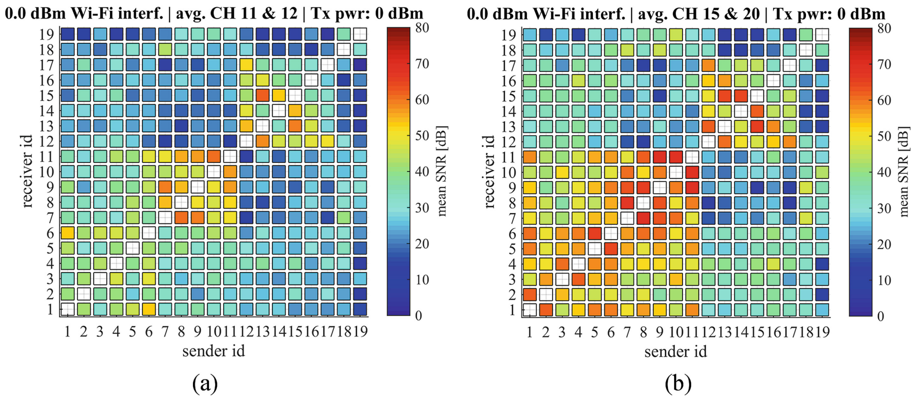
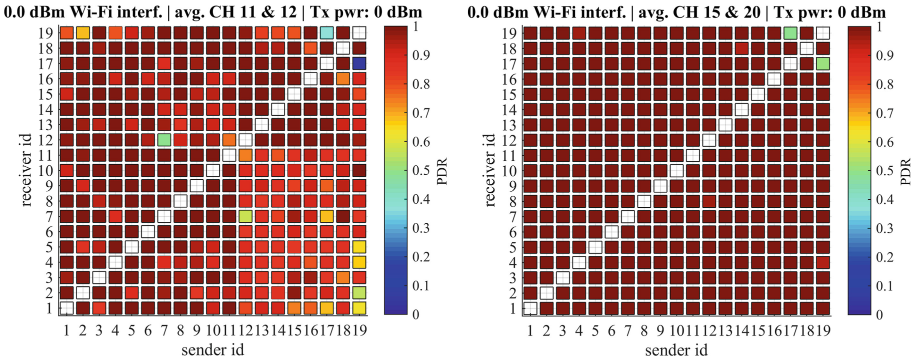


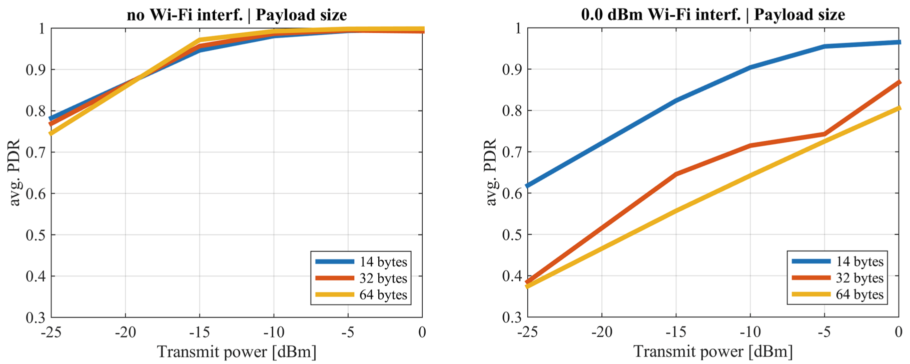
Fig. 7. Average SNR values for the different wireless sensor links for 0 dBm transmit power and with 0 dBm Wi-Fi interference level. (a) IEEE 802.15.4 channel 11 & 12 and (b) channel 15 & 20.



(a) (b)

Fig. 8. PDR values for the different wireless sensor links for 0 dBm transmit power and with 0 dBm Wi-Fi interference level. (a) IEEE 802.15.4 channel 11 & 12 and (b) channel 15 & 20.

The influence of the different packet sizes on the PDR when transmitting at different power levels is shown in Fig. 9. Without Wi-Fi interference the difference between the PDR values for a payload size of 32 and 64 bytes compared to a payload of 14 bytes is less than 3.4%. At 0 dBm Wi-Fi interference, the PDR values of payload sizes of 32 and 64 bytes are close to each other with an average 5% difference. However, compared to the 14 bytes payload size, those PDR values are between 9.74% and 26.7% lower.



(a) (b)

Fig. 9. Average PDR values for the different transmit powers. (a) without Wi-Fi interference and (b) with 0 dBm Wi-Fi interference level.

5.2 Measurement Results for the 2011 Nissan Leaf

The measurements taken on the inside the 2011 Nissan Leaf showed the same zone effect for low power wireless communication as was observed with the 2000 Hyundai Accent GLS, see Fig. 10. However, the distinction between the passenger area and the boot is less strict in the Nissan than for the Hyundai.

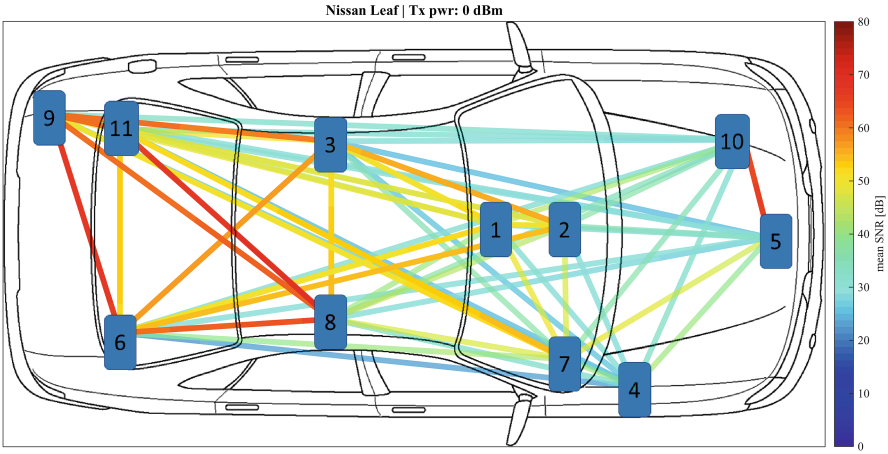


Fig. 10. Average SNR values for the different wireless sensor links for 0 dBm transmit power and without Wi-Fi interference

5.3 Measurement Results of the Engine Section

The influence of the engine (petrol or electric) on the low power wireless communication was first measured with the engine off and then with the engine on while driving.

For the petrol engine of the 2000 Hyundai Accent GLS, we did not observe significant differences in the average SNR values between driving or parking, the difference is less then 0.79%, but the PDR was reduced during driving (see Figs. 11 and 12). Mostly the communication between nodes ID 1, 2 and 3 was effected. This could possibly result from the engine noise during the driving which increases the bit error rate and packet drops. The same behaviour was also observed in [8].

However, for the 2011 Nissan Leaf, the impact on the average PDR over all IEEE 802.15.4 channels while driving was more obvious (see Fig. 13). The charging phase after the driving measurements had an effect on the average PDR for IEEE 802.15.4 channels 11 and 12. Figure 14 shows the PDR for the IEEE 802.15.4 channel 12 with the engine off and during the charging phase. The PDR of the links between the node ID 1 and node ID 3 & 4 is more than 70% reduced during the charging phase.

This noise could be produced from the battery charging unit and the high currents during the charging phase.

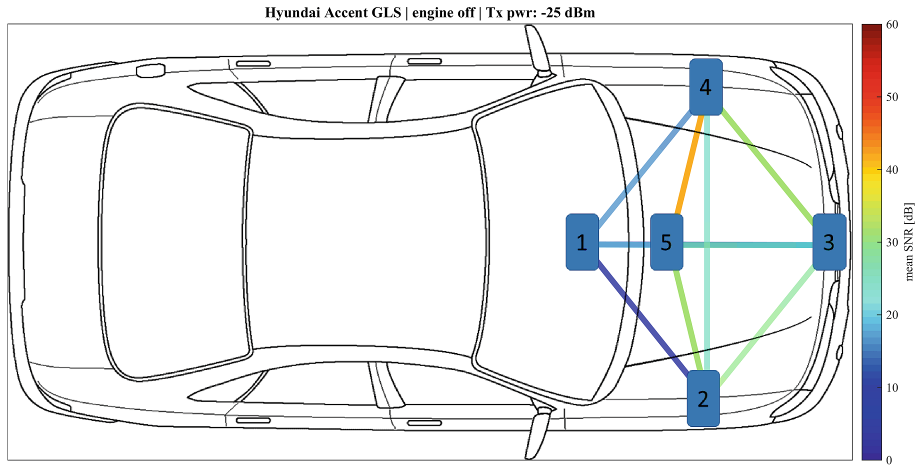


Fig. 11. Average SNR values for the different wireless sensor links for −25 dBm transmit power and engine off

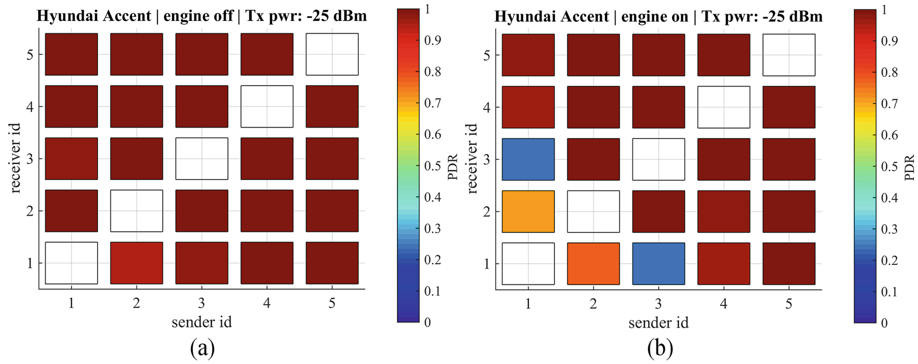


Fig. 12. Average PDR values for the different transmit powers. (a) Engine off and (b) Engine on.

5.4 Vehicle Zones

The different zones within the vehicles with similar wireless channel behaviour are shown in Fig. 15. They are the engine section, the passenger area and the boot. The two wireless sensors (Sensor ID 18 and 19) at the rear tyres show no specific link to any of the zones. The authors in [4] observed similar zones with UWB communication within the vehicle. We observed in both vehicles that the average SNR of the wireless sensor links within the zones are around 66% higher compared to other wireless sensor links.

One major advantage of splitting the vehicle into different zones is to reduce the complexity of a intra-vehicle wireless channel model. The model can take into account the zone specific influences such as an empty or heavily loaded

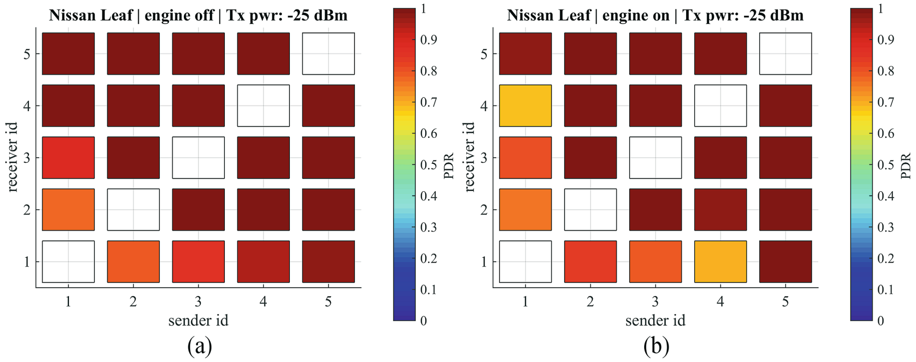


Fig. 13. PDR values for the different wireless sensor links for -25 dBm transmit power. (a) Engine off and (b) Engine on.

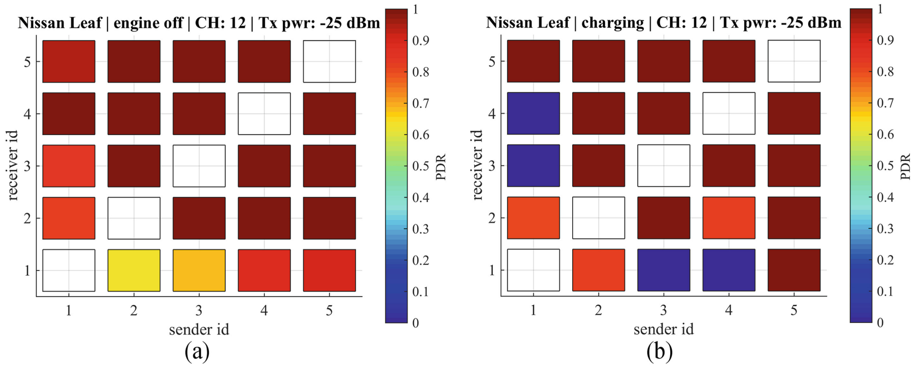


Fig. 14. PDR values for the different wireless sensor links for -25 dBm transmit power for the IEEE 802.15.4 channel 12. (a) Engine off and (b) Charging phase.

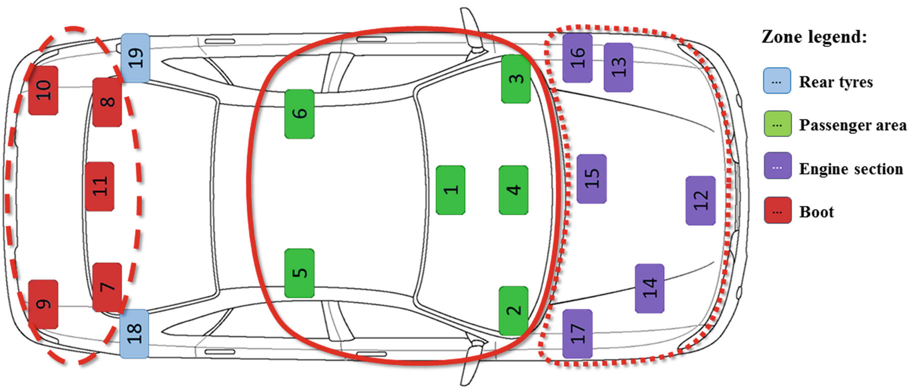


Fig. 15. The different zones inside the vehicle with similar channel behaviour.

boot, one or more passengers or different types of engine. It could also help to develop different packet routing strategies for the different zones, e.g. different priorities for each zone or more than one gateway.

6 Conclusion and Future Work

From the measurements it can be concluded that it is possible to split the wireless sensor network inside the vehicle into different zones which have similar wireless channel behaviour. This simplifies the development of the intra-vehicle wireless channel models and special routing protocols, which take the higher SNR within the zones into account. This insight can be used to further improve communication protocols for intra-vehicle low power wireless communication where so far it has generally been assumed that the channel behaviour is equal throughout the entire vehicle.

In order to judge where to position a gateway or base station for the wireless sensor network, the location of node ID 1 shows the highest PDR (avg. 97.7% PDR) in all scenarios. It is beneficial to reduce the packet size to increase the PDR for all wireless communication. Further research should be carried out to investigate the effect of the different charging rates of an electric vehicle on low power wireless communication. A realistic wireless channel model for the intra-vehicle low power wireless communication based on our study will be developed. This wireless channel model will help to support and further enhance research on communication protocols for intra-vehicle wireless sensor communication.

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